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ONLINE INTEGRATED MODELING ON REGIONAL SCALE IN NORTH-WEST RUSSIA: EVALUATION OF AEROSOLS INFLUENCE ON METEOROLOGICAL PARAMETERS

ABSTRACT. In this study the aerosols influence on selected meteorological parameters during two summer 2010 periods is evaluated with focus on the North-West Russia and urban area of St. Petersburg. For that, the seamless fully online-integrated Enviro-HIRLAM model is used. The simulations are realised in short- and long-term modes for selected periods. For evaluation of aerosol influence, in addition to the control/ reference run, the runs with direct, indirect and both combined aerosol effects are performed.

It was found that for the North-West Russia region, the direct aerosol effect had increased air temperature (by 1-3°) and decreased total cloud cover (by 10-20%). The indirect effect decreased temperature (by 0.4-1°) and increased cloud cover (by 10-20%). The combined effect was the largest territorially; and such effect both decreased temperature and cloud cover (by 1-3° and by 6-20%, respectively) as well as increased these (by 0.4-0.6° and 10-20%).

KEY WORDS: aerosols influence, Enviro-HIRLAM, online integrated modelling, North-West Russia

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INTRODUCTION

In the 21st century, the industrial development has reached higher levels. In particular, almost all large cities of Russia have own industrial enterprises. These produce large amounts of anthropogenic emissions. For megacities, there are several sources of these emissions such as transport, energy and heating production from combustion, etc. Among pollutants, many can have influence on living standard of humans as well as can influence the environment.

In this study, the evaluation of pollutants influence, in particular, on spatio-temporal distribution of aerosols on meteorological parameters (on example of the North-West Russia (NW RU) as well as the St. Petersburg metropolitan area) was carried out. It has been realized through the online integrated modeling and analysis of aerosols influence on regional and megacity scales (Nerobellov 2017).

Aerosols are little solid or liquid particles with sizes in interval from 10^{-3} to $100\ \mu\text{m}$. These particles can be of natural as well as anthropogenic origin. Usually aerosols influence is divided into direct aerosol effects (DAE) and indirect (IDAE). The direct influence is reflected in aerosol dispersion and absorption of solar and heat radiation that can lead to changing in the Earth's radiation balance. The indirect influence is represented in changing of radiative properties and life cycle of clouds (due to aerosols) and after all in influence on radiation balance. These aerosol types of effects were studied and discussed by Beresnev and Gryazin (2008); Ginzburg et al. (2009); Ivlev and Dovgaluk (1999).

MATERIALS AND METHODS

Research domains in focus

Saint-Petersburg is the biggest industrial center of Russia. There are a few continuously working engineering enterprises on territory of the city, but the main sources of pollution are transport related with traffic emissions (about 86% of all). In 2013 this city was claimed as one of the most polluted among

Russian cities. It was decided to choose NW RU and the St. Petersburg metropolitan area for estimating of aerosols influence on main meteorological parameters (such as air temperature at 2 m and total cloud cover) on regional scale and with zoom to the metropolitan area.

Selected meteorological periods

In our study, the focus was on a season with a weak wind speed and anticyclonic weather conditions. In particular, the abnormally hot weather over the studied region was observed in summer 2010, and it was caused by a blocking anticyclone (Ovanessian et al. 2010a-c). Such meteorological conditions led to large-scale forest fires on the territory of the European Russia. Therefore, this summer was chosen to perform online-integrated simulations (in particular, for short-term study - 10-12 July and for long-term - 1-30 August 2010). Dominated anticyclonic weather conditions in summer 2010 could underline on how aerosols influenced on selected meteorological parameters such as the air temperature at 2 m (direct effect). In addition, there was a possibility for observing aerosols influence on cloudiness (indirect effect). Also, the large-scale forest fires, which occurred during summer 2010, were significant sources of natural aerosols. This could intensify aerosols influence on considered meteorological parameters.

Seamless/ online-integrated Enviro-HIRLAM modelling

The Environment-High Resolution Limited Area Model (Enviro-HIRLAM) is developed as a fully online-integrated numerical weather prediction (NWP) and atmospheric chemical transport (ACT) modelling system for research and joint forecasting of meteorological, chemical and biological weather. For more information about Enviro-HIRLAM modeling system and modules (with corresponding references) see in Baklanov et al. (2017). This model is capable to provide forecast of multiple meteorological fields such as air temperature, relative and specific humidity, atmospheric pressure, wind speed and direction, cloud cover, turbulent kinetic energy, etc. based on

forward in time integration of the primitive equations and physical processes such as radiation, vertical diffusion, convection, condensation and others. This integrated modeling system was originally developed by the Danish Meteorological Institute (DMI) in a cooperation with several European universities (and since May 2017 it continued to be developed at the University of Helsinki, UHEL, Finland), and it is used in various applications. General block-scheme of the Enviro-HIRLAM system is shown in Fig. 1.

The Enviro-HIRLAM model was employed to perform simulations for both short- and long-term periods. In particular, the simulations were done for period 1-30 Aug 2010 as well as for selected episode with the unfavorable meteorological conditions. This episode is: 10-12 Jul 2010. The model setup includes: horizontal resolution of 15 km, 40 vertical levels, time-step of 360 sec.,

meteorological data assimilation – every 6 hours, output – every 3 hours (GRIB and netCDF formats). For the NW Russia region in focus, 4 runs of the model were performed: CTRL (or control/reference run, e.g. without any aerosol effects included), DAE (direct aerosol effects), IDAE (indirect aerosol effects) and COMB (combined, where direct and indirect aerosol effects included). The analysis focused on evaluation of aerosol influence on selected key meteorological parameters such as the air temperature at 2 m (T2M) and total cloud cover (TCC).

RESULTS AND DISCUSSIONS

The aerosols influence on the meteorological parameters was estimated on the regional scale (with focus on the NW Russia territories) as well as by zooming down to the Saint-Petersburg metropolitan area.

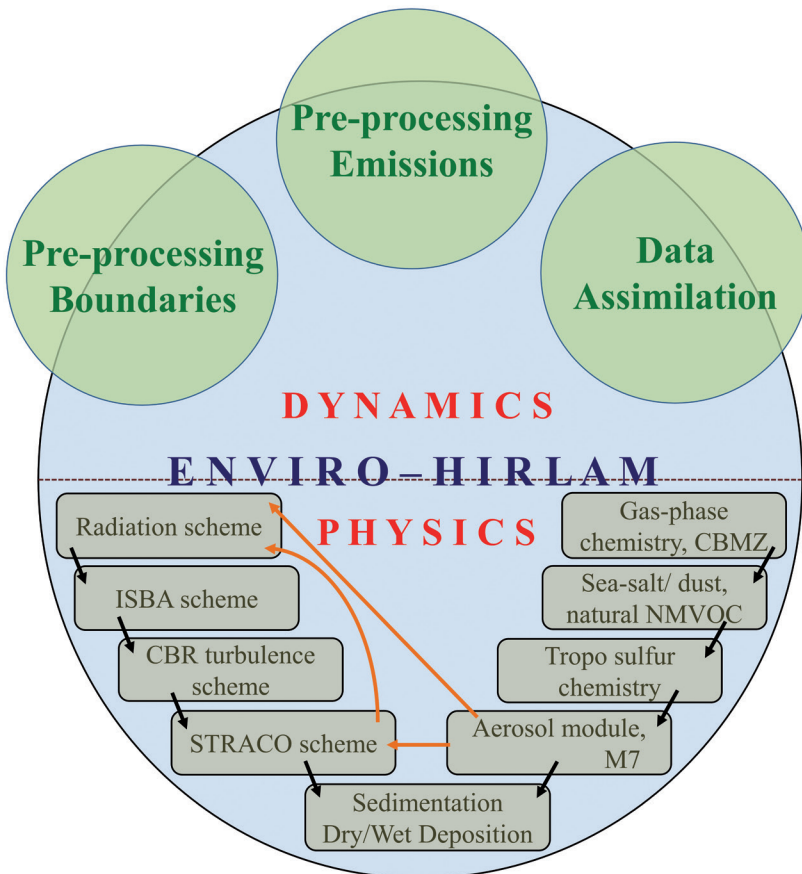


Fig. 1. Flow chart of the Enviro-HIRLAM modelling system

Aerosols influence on meteorology on regional scale: case study 10-12 July 2010

For the air temperature at 2 m (almost all domain - AIAD seen on Figs. 2-3, top-center) the direct aerosol effect influence was significant in the south-east, north-west and west areas of the domain in focus. Such influence led to the temperature decrease (on 2-3°C) on the west. In addition, there were large areas with the temperature decrease (1°C) on the north - between the Gulf of Bothnia and the White Sea. A few small areas can be distinguished and one large, where the temperature increased (1-2°C) on the east and south-east. In case with the indirect effect, the influence on the temperature was negligible, and therefore, it was not included in this figure. The most significant changes of the temperature values can be observed in the northern part of the domain. Large areas (with decrease on 1-2°C) were observed there (see Fig. 3-top-left). The combined effect (Figs. 2-3, top-right) showed a merging of the temperature changes from both the direct and indirect effects (decrease on 1-3°C: west and north; and increase on 1°C: east and south-east). Nevertheless, there were some little differences from both of these effects (for example, influence zones on the north and

west were wider, than in case of the direct and indirect effects).

As seen (Fig. 2, bottom-center) with the direct effect the most significant changes (decrease on 10-30%) in the total cloud cover were in the northern, eastern and south-eastern parts of the research domain. The indirect effect also was significantly weaker than the direct and combined, and therefore, it was not included in the Fig. 2 (bottom). In this case, the TCC increased in the northern part (10-30%) and decreased in the north-eastern (40%). The combined effect (Fig. 2-3, bottom-right) included several zones with the direct and indirect effect influences. However, all these zones became wider in the size, and the values became larger in the case of the combined effect (decrease on 10-40%: south-east and east; and increase on 10-50%: northern part and west).

Aerosols influence on meteorology with zoom to St. Petersburg: case study 10-12 July 2010

The indirect effect influence on the air temperature at 2m and the total cloud cover with a zoom to St. Petersburg was insignificant; so it was not included in Fig.

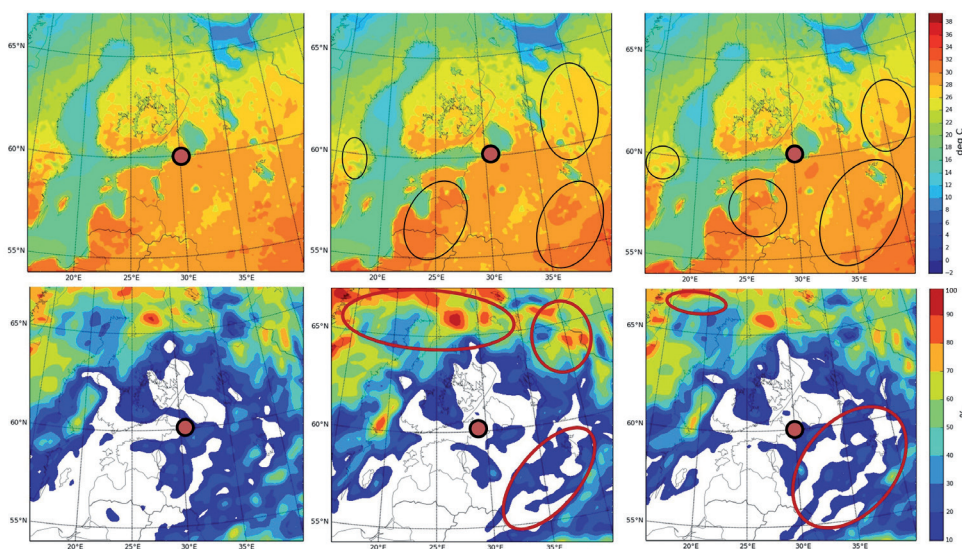


Fig. 2. 3-day (10-12 Jul 2010) averaged (top) air temperature at 2 m (T2M) and (bottom) total cloud cover (TCC) fields at 12 UTC for the Enviro-HIRLAM model runs: reference/control (CTRL), with direct aerosol effect (DAE) and combined aerosol effect (COMB) included (from left to right)

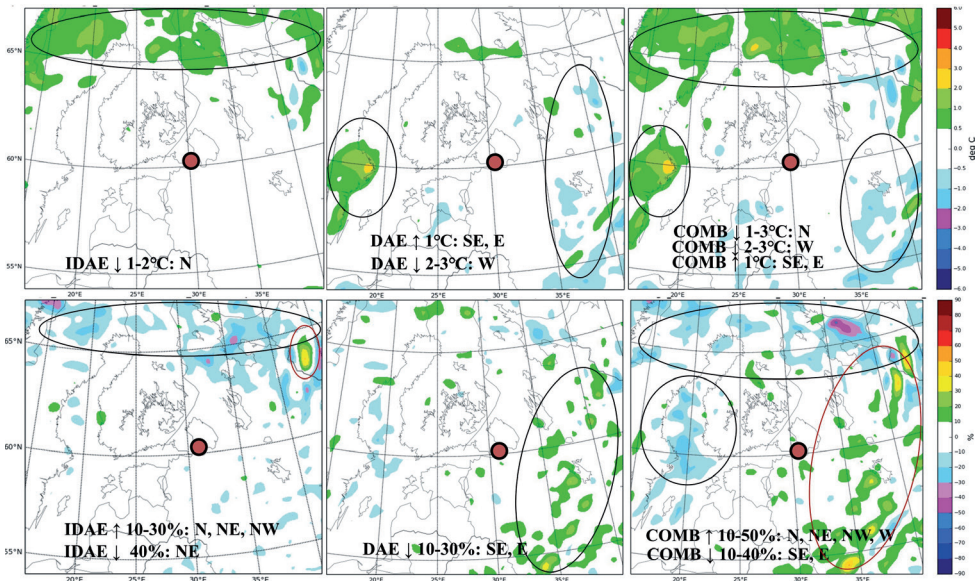


Fig. 3. 3-day (10-12 Jul 2010) averaged (top) air temperature at 2 m (T2M) and (bottom) total cloud cover (TCC) fields of differences at 12 UTC for the Enviro-HIRLAM model runs: reference/ control-indirect aerosol effect (CTRL-IDAE), control-direct aerosol effect (CTRL-DAE) and control-combined aerosol effect (CTRL-COMB) (from left to right)

4. As it can be seen on Fig. 5 (top-left), the indirect effect was mostly reflected as the temperature decrease, but also the increase was observed. For example, it was decreased on the south and south-east (on 0.4°C), and increased - on the east (0.4°C). The direct effect influence (Fig. 4-5, top-center) was stronger than the indirect. Mostly it was observed in the eastern part of the research area. This effect increased T2M on the south-east, east and north (0.8°C) and decreased on the west (0.4°C) of the domain. The combined effect influence (Figs. 4-5, top-right) was almost similar to the direct effect. The main differences between these were in the widening of sizes of the influence zones and the values inside were higher in the case of the combined effect. This effect decreased the temperature on the west and north-east (0.4°C) and increased in the eastern and northern parts (on 0.4-1.0°C).

In the case of the TCC, the indirect effect (Fig. 5, bottom-left) increased it (3-15%) on the south, south-west, north-east, east; and decreased (3-6%) on the south-east. The direct effect (Figs. 4-5, bottom-center) led to decrease in most of the cases. It decreased the cloud cover by 3-18% on the north-

east, north, south-east and south-west of the domain. The combined effect (Figs. 4-5, bottom-right) was similar to the direct effect, and it led to the TCC decrease (6-21%) on the north-east, north, south-east and south-west. But the zones of influence for the combined effect were wider and the values inside these were higher. This effect was stronger than the direct and indirect effects.

Aerosols influence on meteorology on regional scale: long-term period of August 2010

Evaluating the monthly averaged results, it was found, that the indirect effect (Fig. 6-top-center) looked like in the reference run for the air temperature at 2 m. The most significant indirect influence can be seen in the center and in the eastern and northern parts of the domain, where the temperature decreased. For the total cloud cover (Fig. 6, bottom-center), the indirect effect increased values almost within all research area. The direct effect also decreased T2M (Fig. 6, top-right) in the center and eastern part. For TCC (Fig. 6, bottom-right) it was weaker than the indirect influence, and it can be seen in the southern part, where the cloud cover decreased.

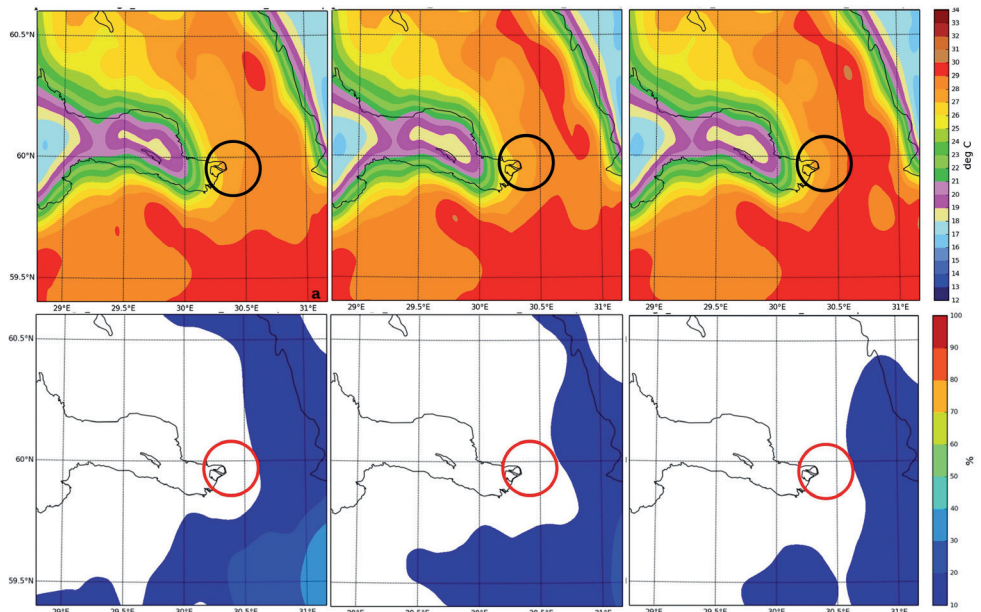


Fig. 4. 3-day (10-12 Jul 2010) averaged (top) air temperature at 2 m (T2M) and (bottom) total cloud cover (TCC) fields at 12 UTC for the Enviro-HIRLAM model runs: reference/control (CTRL), with direct aerosol effect (DAE) and combined aerosol effect (COMB) included (from left to right)

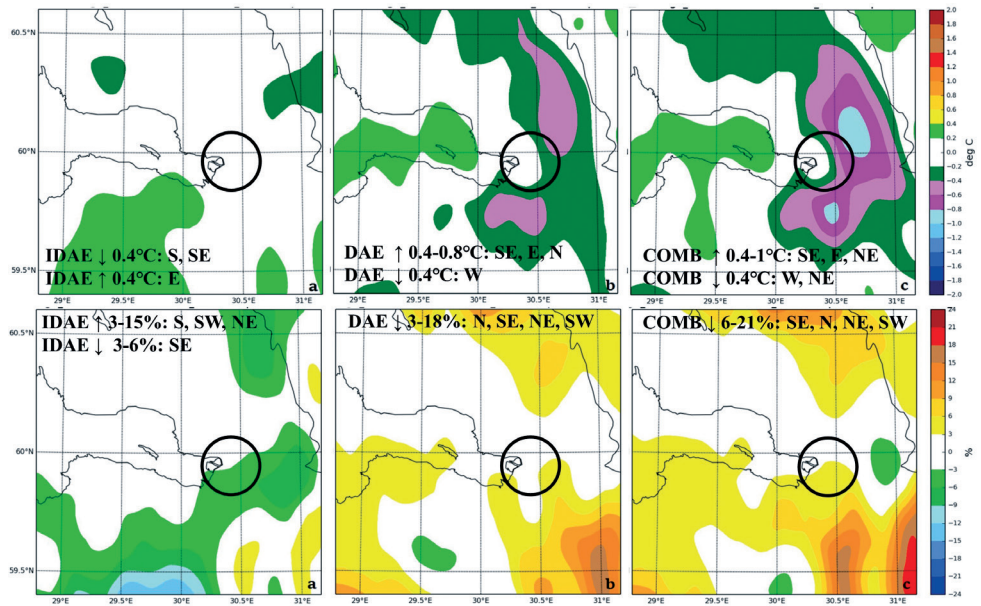


Fig. 5. 3-day (10-12 Jul 2010) averaged (top) air temperature at 2 m (T2M) and (bottom) total cloud cover (TCC) fields of differences at 12 UTC for the Enviro-HIRLAM model runs: reference/control-indirect aerosol effect (CTRL-IDAE), control-direct aerosol effect (CTRL-DAE) and control-combined aerosol effect (CTRL-COMB) (from left to right)

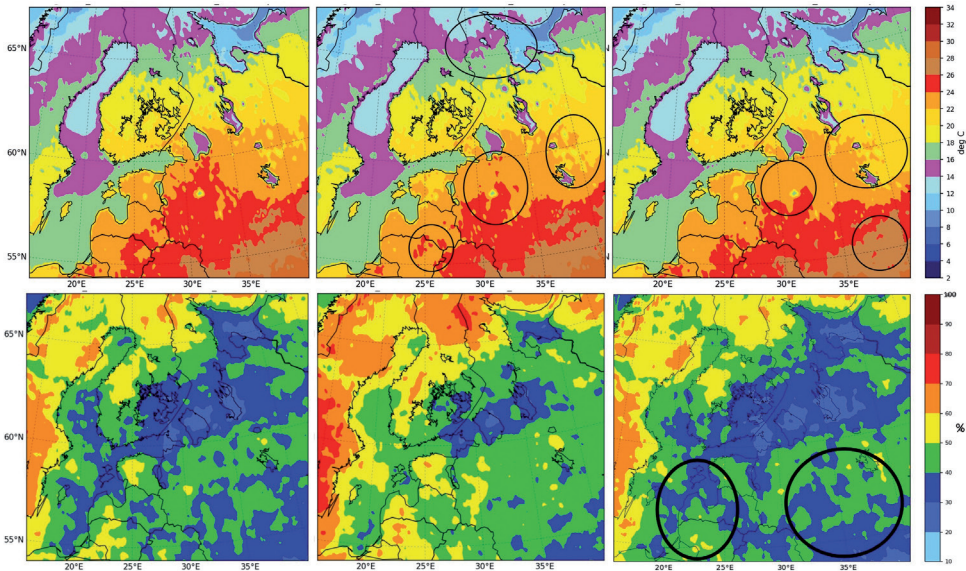


Fig. 6. Monthly (Aug 2010) averaged (top) air temperature at 2 m (T2M) and (bottom) total cloud cover (TCC) fields at 12 UTC for the Enviro-HIRLAM model runs: reference/control (CTRL), with indirect aerosol effect (IDAE) and direct aerosol effect (DAE) included (from left to right)

A more detailed information is presented in Fig. 7 showing differences between the model runs, and here, more peculiarities can be identified. For example, for the indirect effect the air temperature in general decreased (on 0.4-0.8°C) in the northern and western parts (Fig. 7, top-left). At the same time the cloud cover increased (3-20%) within all research area, mainly on the north and west (Fig. 7-bottom-left). For the direct effect it can be noticed, that T2M (Fig. 7-top-right) decreased (0.4-2.4°C) in the northern part with the temperature growth (1.2°C) on the south-east. The cloud cover (Fig. 7-bottom-right) decreased (3-12%) by the direct effect mostly on the north, south-east and south, but also it increased (3-12%) on the south-east.

For further analysis, let's write hours (h) thereafter as the equivalent of UTC (universal coordinated time). As it can be seen from the Table 1, the direct effect (DAE) mainly influenced on the south-east area of the domain in focus, where it decreased the air temperature on 1.6-3.2°C and increased on 0.8-2.8°C, relatively to the reference case. The temperature decreased during night-time hours (00-06) and during time period after 12 h (12-15 h). This effect also increased

temperature during the second part of the day (12-21 h). The maximum increase (on 2.8°C) was noticed at 21 h on the south-east. The maximum decrease (3.2°C) was observed at 06 and 15 h on the east and south-east. Let's consider the boundaries of the zones of increase (Zol) and the zones of decrease (ZoD) as a widening and narrowing in the size, respectively. For the air temperature, the Zol became larger from 12 to 21 h and smaller from 00 to 06 h; and the ZoD became larger in size from 00 to 09 h and smaller - from 12 to 18 h.

For the indirect effect, the observed changes were mostly insignificant (NoSC), except during hours 00, 12 and 18-21 h. Basically the indirect effect influenced in the northern and southern parts of the research area. The temperature growth on 0.8-1.2°C was observed in the south-east, and north, and the temperature drop on 0.4-0.8°C was observed in the northern part and central zone. In addition, it can be noticed, that Zol appeared and became wider after 18 h and then smaller - after 21 h. The zones of ZoD became significantly wider at 12 h and almost disappeared after 18 h.

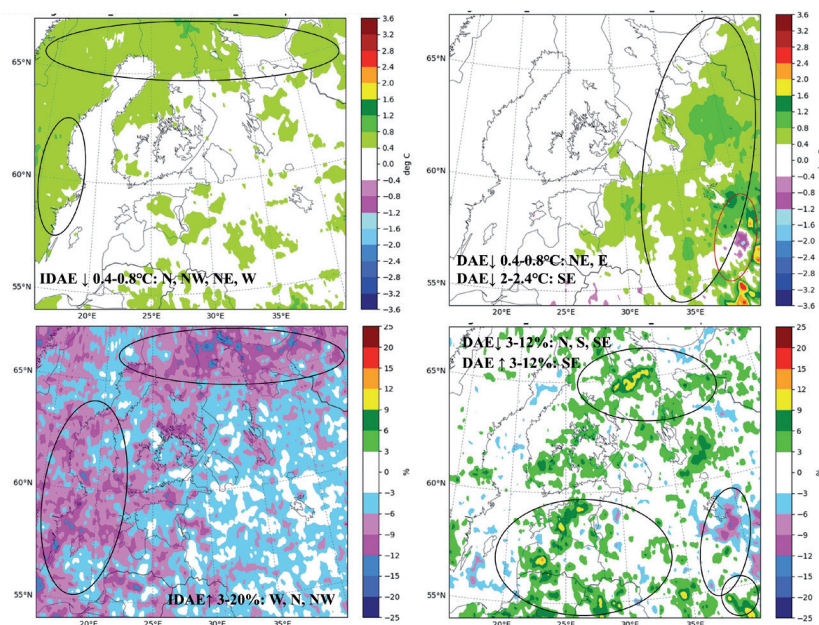


Fig. 7. Monthly (Aug 2010) averaged (top) air temperature at 2 m (T2M) and (bottom) total cloud cover (TCC) fields of differences at 12 UTC for the Enviro-HIRLAM model runs: reference/ control-indirect aerosol effect (CTRL-IDAE), control-direct aerosol effect (CTRL-DAE) (from left to right)

Table 1. Diurnal cycle variability (averaged over 1-30 Aug 2010) of the air temperature at 2 m (T2M) changes due to direct (DAE) and indirect (IDAE) aerosols effects / comments: no significant changes – NoSC; zone of increase – ZoI; zone of decrease – ZoD; central zone – CZ; almost all domain - AIAD/

Term (UTC)	DAE-Direct Aerosols Effect			IDAE-Indirect Aerosols Effect		
	Zones of the most significant influence	Type (↑↓) and value (±°C) of influence	Tendency	Zones of the most significant influence	Type (↑↓) and value (±°C) of influence	Tendency
00	SE	↓1.6 ↑2.4	NoSC	N	↓0.8	NoSC
03	SE	↓1.6 ↑0.8	ZoI – smaller ZoD – wider	NoSC	NoSC	NoSC
06	E, SE	↓3.2	ZoD – wider ZoI – disappeared	NoSC	NoSC	NoSC
09	SE	↓3.0	ZoD – wider	NoSC	NoSC	NoSC
12	E, SE, SE	↓2.8 ↑1.2	ZoD – smaller ZoI – appeared	NW, NE, CZ	↓0.4	ZoD – wider
15	SE	↓3.2 ↑1.2	ZoD – smaller ZoI – NoSC	NoSC	NoSC	NoSC
18	SE	↓3.0 ↑2.0	ZoD – almost disappeared ZoI – wider	S, SE	↑1.2	ZoI – wider ZoD – almost disappeared
21	SE	↓2.0 ↑2.8	ZoI – wider	SE, N	↑0.8	ZoI – smaller

As it can be seen in the Table 2, although mostly of cases on a diurnal cycle the direct effect increased the total cloud cover (ranging from 3 to 12%) in the domain, and during 06-18 h in some areas from 9% (06 h) and up to 12% (12-18 h). The largest changes (12%) in TCC due to this effect were observed during 12-18 h and practically in all areas of the domain. Note, that the increase was predominantly observed during evening and nighttime hours in the western part. The tendency of the aerosol effect was not significant at midnight, although it has well pronounced variability on a diurnal cycle. In particular, both zones (Zol and ZoD) became wider at 12 h, and smaller in size - at 15 h; moreover, the zone of decrease almost disappeared at the late evening hours.

The indirect effect increased TCC almost within all research domain. The areas with the most significant influence were located in the northern and western parts of the domain. The cloud cover increased from 00 to 18 h (on 15-20%) and then decreased at 21 h (down to 15%). As in case with the direct influence for TCC, the indirect influence was

stronger at afternoon hours (12-18 h) and weaker in other hours on a diurnal cycle. For TCC, the indirect effect was stronger, than the direct. The tendency of the aerosol effect was insignificant at midnight time. In general, the Zol zones were smaller during 21-03 h and were wider during 12-18 h. As the TCC field can not be represented by a continuous function due to irregularities in the cloud cover distribution, the tendency of the aerosol influence and its magnitude can depend on how rapidly and in which direction the cloud systems can move. Therefore, tendency of the aerosol influence on TCC can vary in time and space stronger than on temperature field.

CONCLUSION

In this study, the main aims were to evaluate the aerosol influence on the meteorological parameters on example of the North-West Russia with zoom to the St. Petersburg metropolitan area. The modelling of the aerosols influence on the meteorological parameters (such the air temperature at 2 m and total cloud cover over selected areas in

Table 2. Diurnal cycle variability (averaged over 1-30 Aug 2010) of the total cloud cover (TCC) changes due to direct (DAE) and indirect (IDAE) aerosols effects / comments: no significant changes – NoSC; zone of increase – Zol; zone of decrease – ZoD; central zone – CZ; almost all domain – AIAD/

Term (UTC)	DAE-Direct Aerosols Effect			IDAE-Indirect Aerosols Effect		
	Zones of the most significant influence	Type (↑↓) and value (±%) of influence	Tendency	Zones of the most significant influence	Type (↑↓) and value (±%) of influence	Tendency
00	W	↑9	NoSC	NW, N, SW	↑15	NoSC
03	W	↑6	Zol – smaller	NW, N, SW	↑15	Zol – smaller
06	SE, N, CZ, W	↓9 ↑3	Zol – smaller ZoD – wider	NW	↑15	Zol – wider
09	N, S, CZ	↓9	ZoD – wider	NW, N, W	↑15	Zol – smaller
12	AIAD	↓12 ↑12	ZoD – wider Zol – wider	NW, N, W	↑20	Zol – wider
15	AIAD	↓12 ↑12	ZoD – smaller Zol – smaller	N, NW, NE	↑20	NoSC
18	S, N, CZ, E, SW	↓12 ↑12	ZoD – smaller Zol – wider	N, NW, NE, SE	↑20	Zol – wider
21	W, SW	↑6	Zol – smaller ZoD – almost disappeared	W, NW, NE, SW	↑15	Zol – smaller

focus) was performed using Enviro-HIRLAM modeling system in both the short- and long-term modes. These simulations were realized for the short-term (i.e. case studies with the most unfavorable meteorological and air pollution conditions) and long-term periods chosen for modeling over the North-West Russia (i.e. 10-12 Jul 2010 and August 2010). The summer periods of 2010 were chosen because of specific weather conditions (high atmospheric pressure, low wind speed) and large aerosols sources such as large-scale forest fires. These factors provided better representation of possible aerosols' influences on selected meteorological parameters. The four simulations were made: control/ reference (CTRL); with the direct aerosol effect (DAE), with the indirect aerosol effect (IDAE), and with both effects included (COMB). The most important findings are the following. The direct effect in most of cases increased the air temperature (1-3°C) and decreased the total cloud cover (10-20%). In contrast, the indirect effect decreased the air temperature (0.4-1°C) and increased the total cloud cover

(10-20%). The combined effect influenced on the meteorological parameters in both ways: decreased the air temperature (by 1-3°C) and the total cloud cover (by 6- 20%) as well as increased the both (0.4-0.6°C, 10-20%) in some areas of the modelling domain.

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